How digital sensors compare to geophones?

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Summary

The advent of MEMS-based digital sensors has been promoted as the next big advance in land seismic acquisition, much like the shift to 24-bits recording systems ten years ago. It is proposed that they can replace geophone arrays and improve quality of P & S wave recording? So, this is a good time to ask the question: Has digital sensor technology really advanced to the point that it can be used for general-purpose land seismic acquisition ? This paper will attempt to answer that question by addressing the advantages and disadvantages of the MEMS-based digital sensors compared to the coiled geophones.

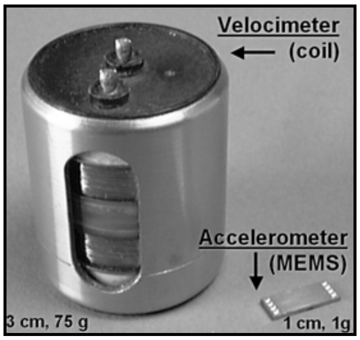

Figure 1: Comparison of a MEMS silicon chip as it is used within digital sensors with the coil/magnet of a geophone.

Introduction

Coil based geophones are a proven technology that has been providing for long the industry with rugged, cheap and self powered sensors. However with the requirement of more quantitative seismic, the need for lighter, broader band and better calibrated sensors is emerging. Land crews with high channels count (4,000+) and large arrays (e.g. 72 geophone arrays) have more and more difficulties to set up and handle large collections of phones (e.g. 400,000+). In addition the renewed interest for multi-component recording call for new type of 3C receivers with a tight integration between field electronics and sensors. All these trends have incited manufacturers to develop and market new digital sensors based on micro electro mechanical system accelerometers (MEMS).

Digital accelerometers vs. analog velocimeters

MEMS-based digital sensor are based on accelerometers that work below their resonant frequency, while coiled geophone are velocimeters that work above their resonant frequency. This difference provide the two types of sensor with quite different dimensions and specifications.

Ground motion can be measured as displacement, velocity, or acceleration. A mass/spring assembly is used for all these measurements. With a soft spring, the mass (the coil in the geophone) does not move and represents the reference for displacement or velocity measurements. With a stiff spring, the mass moves with the case, but with a small residual displacement related to the acceleration. This acceleration can be measured either by the strain on the spring (e.g. low cost, low power, high distortion air bags) or by a feedback force applied to the mass to cancel the displacement (e.g. high performance MEMS-based digital sensors requiring power supply).

In this last implementation the sensor based on MEMS is still analog, while the control loop and the output provided by an application specific integrated chip (ASIC) are digital. Such a "digital" sensor is much smaller than the current geophone (Figure 1). A MEMS accelerometer is a tiny silicon chip with a length of ~1 cm and weighing less than 1 g. A coil-based velocimeter is a cartridge with a length of 3 cm and weight of ~75 g. Within the MEMS, the residual displacement between the inertial mass and the frame is on the order of a few nanometers, while the motion of a geophone coil may reach 2 mm.

From the specification point of view, the essential benefit of MEMS accelerometers is a broadband linear amplitude and phase response that may extend from 0 (DC) to 800 Hz within $\pm$1% in amplitude and $\pm$20 µs in time. MEMS resonant frequency is far above the seismic band (1 kHz). This makes it possible to record frequencies below 10 Hz without attenuation, including the direct current related to the gravity acceleration. The gravity vector provides a useful reference for sensitivity calibration and tilt measurement (3C sensor). Since acceleration increases with frequency (at constant velocity), MEMS accelerometers also are excellent for high frequency measurements. In this domain (> 50 Hz) the floor noise of the MEMS is lower than that of the equivalent geophone + station electronics.

These broadband capabilities open the way for improvement in the vertical resolution of seismic data, which depends on the ratio between the maximum and minimum frequencies of the signal ($F_{max}/F_{min} = 2^n$, n being the number of octaves). A MEMS accelerometer is particularly suited for recording low frequency reflections (< 5 Hz) like the ones at the boundaries between the main lithological formations. In this frequency range, the limitation is more on the source side because such low frequency signals is not emitted with a sufficient S/N ratio. Recording high frequency signals is limited by their strong attenuation during propagation. However, MEMS sensors should be able, when buried in a borehole, to listen to microseismic events (~500 Hz) as fluids move in the reservoir during oil and gas production.

The total dynamic range of a 24-bit recording system using MEMS can be up to 120 dB (ratio between the floor noise

at 4 ms sampling rate - 4.5 $\mu m/s^2$- and the maximum signal - 4.5 m/s^2- that can be recorded with less than -90 dB distortion). It is lower than the total dynamic range of the same system using single geophones that should be up to 140 dB (this is also the total dynamic range of the latest 24 bits recording systems). In practical situations (including the distortion generated by a strong signal or noise), the instantaneous dynamic range of a MEMS accelerometer (at least 90 dB) is better than the one of a single geophone (no more than 70 dB, but this may be improved by using groups of geophones). These differences in total and instantaneous dynamic ranges explain why a MEMS-based sensor is more suited to record a weak signal in presence of strong noise (near offsets) while a geophone (and even more a string of geophones) is more effective in recording a weak/deep reflection in presence of low noise (far offsets).
Amplitude calibration of a MEMS sensor and its stability over aging and temperature variations are better than that of traditional geophones. Overall, the performance of 1C or 3C digital sensors, in which MEMS's are integrated with the station electronics, is better than that of conventional station electronics connected during the same survey to different strings of geophones of variable characteristics.

Benefits of the full digital transmission

Another difference between digital sensors and geophones is the absence of analog transmission. By integration of the station electronic with the MEMS sensor the transmission becomes fully digital.
In the early 1970s, the A/D conversion of the first digital recording system was implemented in the central unit. One analog pair of wires for each channel was used for transmission between strings of geophones and the recording truck. Noise from electromagnetic interferences, signal cross-talk, and sensitivity to leakage were common. About 30 years later, the electronics distributed in the seismic network provide digitization close to the geophone groups. Only two pairs of wires are necessary for telemetric transmission of thousands of channels in real time. Sensitivity to leakage is reduced and the digital data are controlled by each node of the seismic network. However, noise may still contaminate the analog signals transmitted through the strings of geophones. This has disappeared with the integration of the sensor with the station electronic as it is done in the digital sensors.
Advantages of the full digital transmission have already been verified. During field tests, records by bunched geophones were compared to digital sensors planted at the same location (Figure 2). Picked up below a high voltage line, 50 Hz is obvious on the shot point recorded by the geophones. On the corresponding F-K diagram, the electro-magnetic noise interferes strongly with signal. This noise does not occur in any of the three components of the MEMS-based sensors due to the full digital transmission.

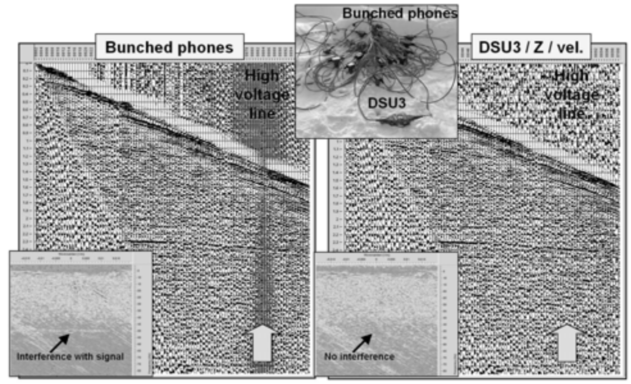

Figure 2: Shot point comparison between digital sensor units (DSU3) and bunched phones (photo). Strong pick up of a high voltage line is due to analog transmission.
(Data courtesy of BNGF)

Single digital sensors to replace geophone arrays?

MEMS-based digital sensors are more expensive than the coiled geophones because each digital sensor includes the station electronics that provides the 24 bits digital output. Therefore, digital sensors must be recorded individually. However this does not prevent, at a later stage (i.e. during processing), to combine these single sensor records by digital group forming to attenuate surface noise.
It is well known that arrays of geophones may tremendously improve the dynamic range of a receiver station by reducing ambient and coherent noise. Compared to a single phone, an array of N geophones, whether connected in series or in parallel, improves the dynamic range by 10 x logN dB, as the ambient noise is reduced by the square root of N. For attenuation of coherent noise, geophones are laid out in a spatial pattern that provides array filtering. The size of the array and the number of wired geophones should be large enough to properly sample the maximum wavelength of the ground roll. Despite these advantages, field geophysicists would like to get rid of these arrays because they are heavy, they slow crew productivity and they require expensive logistics.
At a first glance, the use of single digital sensors would have many operational and geophysical advantages over geophone arrays. Layout and positioning are easier than with geophone strings, and this is even more relevant for 3C receiver points. Recording is isotropic (no azimuth-dependent array filtering), and the high frequency content of the signal is not attenuated by intra-array statics (particularly in S wave recording). However, these benefits are only true in an ideal world where reflected signal is not contaminated by noise, i.e. in a situation where a single coiled geophone would have been sufficient.

How digital sensors compare to geophones?

New requirements for acquisition geometry

In the field, the spacing of single sensors should decrease with respect to the length of a geophone array. This shorter spacing will not attenuate noise while recording, but it will provide enough multiplicity (fold coverage) to decrease the ambient noise while stacking data. Denser spatial sampling also prevents the coherent noise from aliasing. Therefore, we cannot expect to get better looking shot point displays while recording with single digital sensors (Figure 3). The benefits (frequency content, accurate amplitude) will only show up with the final sections, after data processing.

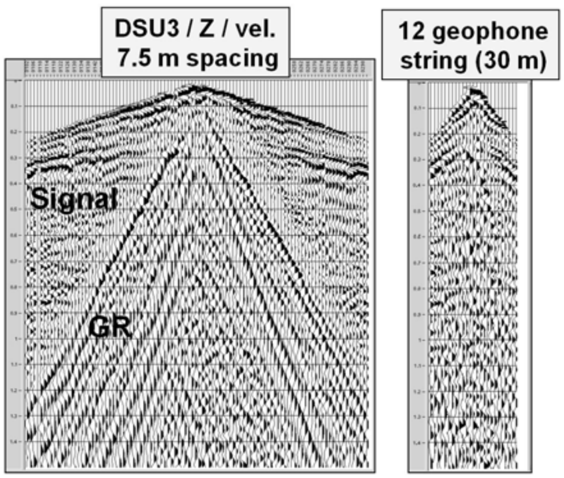

Figure 3: Shot point (GR=ground roll) recorded with single sensor units (DSU) and string of geophones laid out at the same place, but with different spacing. GR is attenuated but it is also aliased on the geophone shot point. (Data courtesy of BNGF).

In practice, how many MEMS sensors would be necessary to replace a string of N geophones? It is unlikely that anyone will record as many single digital sensors as hard-wired geophones, and it is probably not necessary, even though that would provide excellent noise attenuation.

Let us consider ground roll (GR), often the strongest noise. In this case, the digital sensor spacing D should be such that the GR wavelength L=Va/Fa (Va, apparent velocity; Fa, apparent frequency) will be sampled at least two times (i.e. D=Va/2Fa). This often provides values in the range of 3 to 30 m. Figure 4 compares F-K diagrams of two SP's recorded at the same location with different spatial sampling. At 10 m spacing, the very low velocity ground roll (330 m/s which is as low as the air blast) is aliased and interferes with signal. At 3.33 m spacing, GR is still aliased but it vanishes at high frequencies (70 Hz) before intersecting the signal. Considering this maximum frequency limitation of the noise it is possible to adequately sample with a spacing a little more than half of the GR wavelet.

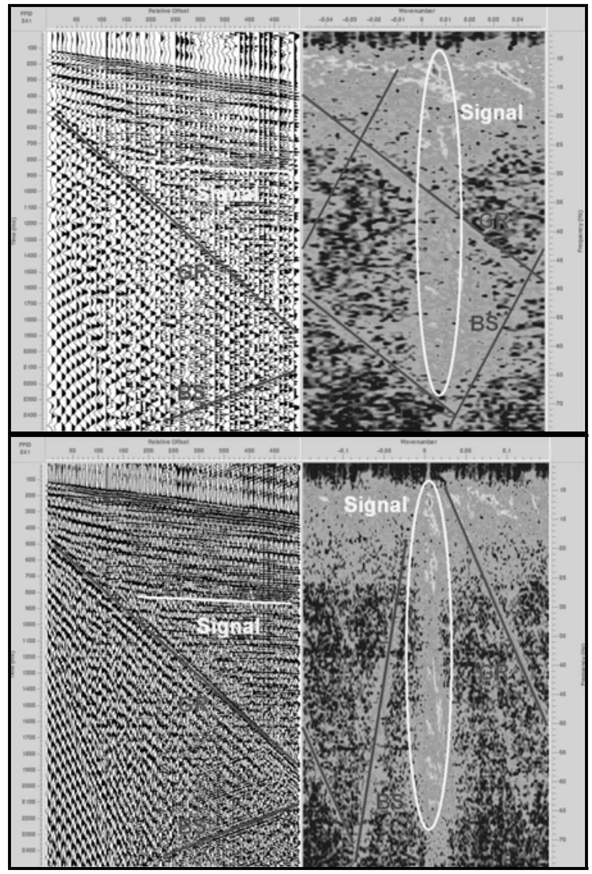

Figure 4: Shot point (GR=ground roll, BS= back scattering) with 10 m spacing (top) and 3.3 m spacing (bottom).
(Data courtesy of CGG)

Up to now, we have considered only 2D propagation. With 3D acquisition or complex near-surface generated backscattered noise, it would be necessary to sample the noise properly both in the inline and crossline directions. Such areal sampling would require a corridor of single digital sensors equivalent to the patches of hard-wired geophones. Since digital sensors are directly connected to a telemetry cable, deployment of such receiver line would require several parallel cables (Figure 5) instead of only one telemetry cable for all geophones. Due to the continuous spatial sampling, this corridor of single sensors provides a sort of 2D universal acquisition design. Different single sensor combinations, often referred as digital group forming, may be used to attenuate noise after recording by all single digital sensors. Since groups overlap from point-to-point, each single sensor may be used in different digital groups. At a given receiver point, this "group forming" may even involve time-dependent digital groups since S/N ratio decreases with travel time.

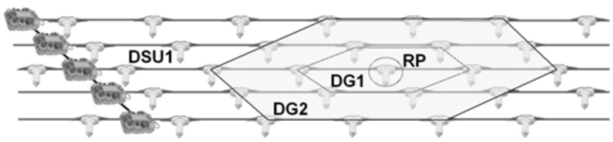

Figure 5: 2D acquisition design that uses single 1C digital sensor units (DSU1) connected along parallel telemetric cables. At a given receiver point (RP) different types of digital groups (DG1, DG2) may be considered to attenuate surface noise.

Conclusions

MEMS-based single digital sensors offer new capabilities compared with conventional arrays of geophones. The sensor itself should provide better vector fidelity thanks to its accurate calibration (amplitude & orthogonality), broadband linear response (from DC to 800 Hz) and low distortion (< -90 dB). Tight integration of the sensor with the station electronics allows size/weight reduction.

For the first time, digital sensors provide complete digital transmission, from the sensor to the central unit, which is less sensitive to electromagnetic pick-up, cross-talk, and leakage. Overall, MEMS technology offers the potential to reduce costs while improving data quality. However, there are two limitations to the use of MEMS sensors: one is geophysical (digital sensors are recorded as single sensors) and the other is economic (manufacturing costs).

If single sensor recording provides obvious advantages for deployment and signal preservation, these benefits are strongly balanced by the inability of single sensors to attenuate any ambient or shot-related noise. Records by single digital sensors will be dominated by noise, and this domination will be even worse if point receivers are used in conjunction with point source (i.e. without any source array filtering). In noisy areas with strong, dispersive and backscattered ground roll and with high ambient noise this may prevent recording any usable signal.

To be able to recover signal, all this noise should be attenuated during processing. For ambient noise reduction, the fold coverage should increase. This is possible by increasing the number of single digital sensors within the same offset range. For coherent noise attenuation, the point receiver spacing should also decrease, down to the Nyquist distance necessary to keep the corresponding ground-roll unaliased (Figure 4). For both ambient and coherent noise reduction, this implies increasing the number of single sensors and the cost of acquiring data.

Up to which limit it would be economical to decrease the spacing of single digital sensors? Let us consider a receiver configuration that should be valid for low noise areas (a six geophone string deployed over 30 m) and assume one single digital sensor (1C or 3C) may replace two geophones or triphones (i. e. the 5 m spacing between phones is replaced by the 10 m spacing between digital sensors). We compare three different configurations equivalent to this 30 m receiver Analog 1C array (Figure 6): the same array where geophones are replaced by triphones (Analog 3C); a line of DSU3 with 10 m spacing (Digital 3C); the same line with DSU1 (Digital 1C).

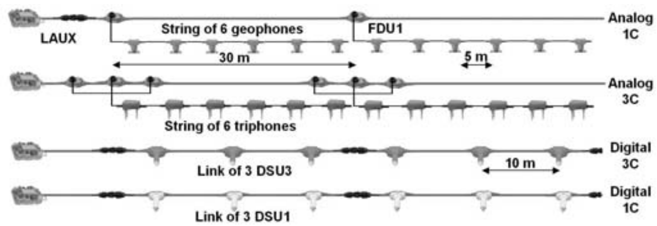

Figure 6: A conventional 6 geophone string receiver point (Analog 1C) is compared with the corresponding Analog 3C receiver point. Assuming one digital sensor may replace two geophones, the corresponding Digital 3C & 1C receiver points are displayed.

As an indicator of capital expenditure (CAPEX) we consider the cost of a 30 m receiver line equivalent to the Analog 1C array (reference of 1). As indicator of operational expenditure (OPEX) we choose the weight of the same 30 m receiver lines compared to the weight of the three other configurations. Cost/weight of the central unit, the crossing units, the line units and the associated batteries are not taken into consideration.

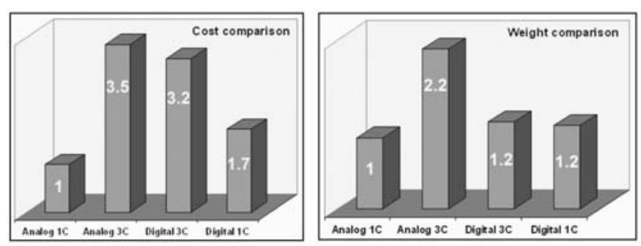

Figure 7: Cost (for CAPEX) and weight (for OPEX) comparison of the four configurations presented in Figure 6. Numbers are relative to the conventional analog 1C configuration (reference = 1).

From the cost/weight comparison in the histograms (Figure 7), two obvious conclusions come up:

- for 3C acquisition it is already cheaper for both CAPEX & OPEX to use a line of 3C digital sensors;
- for 1C acquisition it is more expensive to invest in a dense digital line than in a conventional analog 1C array, but the operational costs are close.

Acknowledgments

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